Sensing

Characterizing Sensors
Pose and Location Sensors
Localization Physics

Some slides adapted from Mark Donovan @ ROBO Business, with thanks
Many slides adapted from slides © R. Siegwart, ETH Zürich – Autonomous Systems Laboratory

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Some Valid Questions

- Why do we need to know what sensors there are?
  - To use, understand, and build robots that can adapt and function flexibly in the world.
- Why do we need to know how they work?
  - Largely, to understand what's going on when they **don't** work.

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Sensing overview

- What's a sensor?
- Characterizing senses:
  - Exteroceptive/Proprioceptive
  - Passive/Active
  - Absolute/Relative
  - Linearity
  - Bandwidth
  - Sensitivity
- Pose and Location

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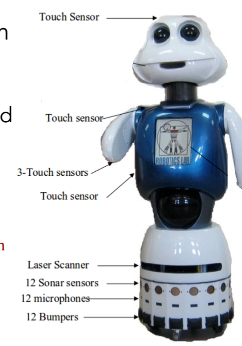
What's a Sensor?

- Anything that gives a system information about its **physical environment**
  - Robots exist in a physical world
- How many can we think of?

sight/RGB, chemicals (gas), bump, texture, temperature, location, pressure, electricity, sound, light, joint encoders, acceleration, taste, range/distance, humidity, etc., etc., etc…

- What does robot need to know?



http://www.mdpi.com/1424-8220/15/7/15799/htm 4

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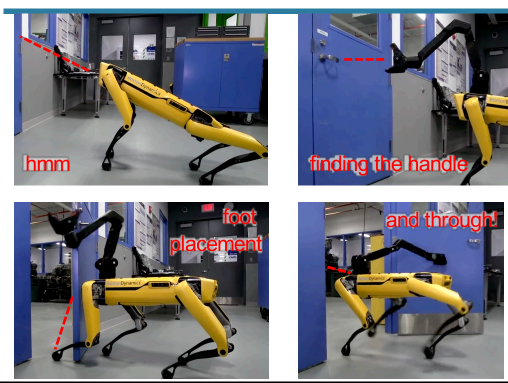
For Example…



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Classification of Sensors

- What do you need to know about a sensor to…
  - **Design** a robot?
  - **Understand** an existing robot?
  - **Use** a robot?
- Characteristics of a sensor
- Six main either/or characteristics
  - Exteroceptive / Proprioceptive
  - Passive / Active
  - Incremental / Absolute

Aldebaran NAO robots

https://newatlas.com/nao-humanoid-robot-aldebaran-robotics/20862 6

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Exteroceptive/Proprioceptive

- **Exteroceptive** sensors
  - Retrieve information from the robot's environment
  - This is most of what we think of when we think "sensors"
  - Examples?
    - camera bump sensors thermometer range finder
- **Proprioceptive** sensors
  - Measure values internal to the system (robot)
  - Just as common and just as important
  - Examples?
    - battery status joint encoders wheel load

Passive/Active

- **Passive** sensors
  - Don't send anything "out"
  - Energy comes from the environment
  - Examples?
    - camera thermometer microphone e-field sensor
- **Active** sensors
  - Emit energy and measure the reaction
  - Better performance, but influences environment
  - Examples?
    - sonar/lidar camera with flash x-rays

Absolute/Relative

- **Incremental** sensors
  - Reports an incremental change (up/down, warmer/cooler)
  - Requires calibration
  - Examples?
    - beacon-based distance magnetic joint encoder
- **Absolute** sensors
  - Unambiguously reports its state
    - Within a known scale or range
  - No need for any reference information
  - Examples?
    - GPS thermocouple range sensor color vision

General Classification (1)

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Tactile sensors (detection of physical contact or closeness; security switches)	Contact switches, bumpers Optical barriers Noncontact proximity sensors	EC EC EC	P A A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders Potentiometers Synchros, resolvers Optical encoders Magnetic encoders Inductive encoders Capacitive encoders	PC PC PC PC PC PC PC	P P A A A A A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass Gyroscopes Inclinometers	EC PC EC	P P A/P

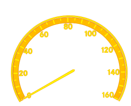
A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

General Classification (2)

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Ground-based beacons (localization in a fixed reference frame)	GPS Active optical or RF beacons Active ultrasonic beacons Reflective beacons	EC EC EC EC	A A A A
Active ranging (reflectivity, time-of-flight, and geometric triangulation)	Reflectivity sensors Ultrasonic sensor Laser rangefinder Optical triangulation (1D) Structured light (2D)	EC EC EC EC EC	A A A A A
Motion/speed sensors (speed relative to fixed or moving objects)	Doppler radar Doppler sound	EC EC	A A
Vision-based sensors (visual ranging, whole-image analysis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

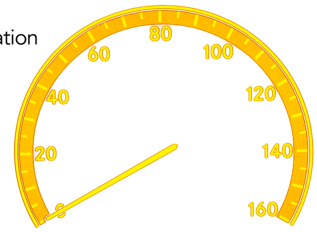
More Characteristics

- Pertaining to the readings (values) returned:
  - Range: How high/low does it go (accurately)?
  - Resolution: How small a change can it report?
  - Linearity: How linear is the response to change?
  - Bandwidth: How fast can readings change?
  - Sensitivity: How much small a change can it pick up?
  - Cross-sensitivity: do readings change based on something other than the intended target?




Range

- Range: what's the range of returnable values?
  - Upper limit, lower limit
- Limited by reality
  - For a degree-of-rotation sensor, range is..?
- Limited by sensor



pixabay.com/illustrations/speedo-speed-speedometer-ad-1772673/

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Resolution

- Resolution: how fine-grained is it?
  - The minimum *measurable* difference
    - Ex: accuracy to ±0.7° F (±0.4° C)

thermoworks.com

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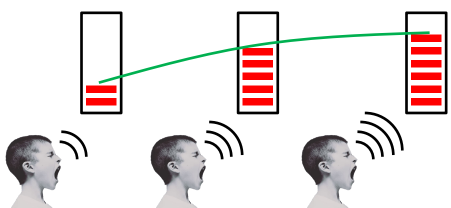
Linearity and Bandwidth

- Linearity
  - Variation of output as function of the input
  - Less important when signal is postprocessed
    - Assuming you know the nonlinear function



www.pxfuel.com/en/free-photo-qyzim

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Linearity and Bandwidth

- Bandwidth or Frequency
  - the speed with which a sensor can provide a stream of readings
  - usually there is an upper limit depending on the sensor and the sampling rate
  - Lower limit is also possible

en.wikipedia.org/wiki/Film_stock#/media/File:16mmBWrevDP.png

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Sensitivity

Especially relevant for real world (uncontrolled) environments

- Sensitivity
  - How much change in world affects change in readings
  - *Ratio* of output change to input change
  - High sensitivity often correlated to high cross-sensitivity
- Cross-sensitivity
  - Sensitivity to environmental parameters unrelated to actual target
  - An SO_2 sensor has a -120% response to NO_2.
    - An SO_2 sensor sees 5ppm of NO_2 at the same time as 5ppm of SO_2, the reading would be reduced by 6ppm, showing 0ppm.

www.crowcon.com/blog/cross-sensitivity-of-toxic-sensors-chris-investigates-the-gases-that-the-sensor-is-exposed-to/

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Some Important Senses: Pose and Location

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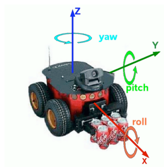
Pose

- **Pose:** How is the robot…
  - Posed: Where are its parts relative to each other
  - Oriented: With respect to an external frame of reference

- Location: where is the robot?
  - With respect to an external frame



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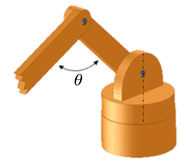
Pose: Encoders

- What does an encoder do?
  - In general, "encodes" motion to an electrical signal
- Almost always encodes rotation.
- In robotics:
  - Joint angles (how "open" is a joint?)
  - Wheel rotations
  - Motor rotations
- Can be absolute or relative
- Can be magnetic, optical, or other



θ = joint angle

http://nptel.ac.in/courses/112103174/module7/lec5/3.h 20

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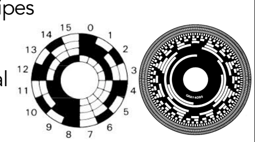
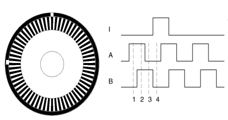
Optical Encoders

- Use a light source + light sensor
  - Plus disk with gaps or dark stripes
- Absolute encoders
  - Every station has unique signal
  - Requires better sensors
- Quadrature encoders
  - Two off-phase sensors
  - Rotation direction





State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

http://transducersensors.com/absolute-encoders, Danaher Industrial Controls—Dyna 21

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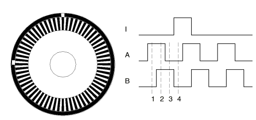
Quadrature Encoders

- Wheel and motor (and usually joint) encoders
- Reading: where in its rotation are they?



State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

- Basically same as optical mice/trackballs

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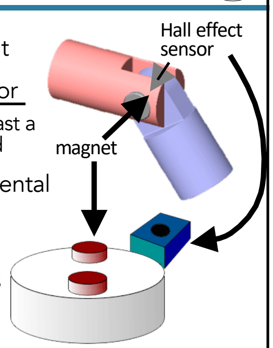
Magnetic Encoders

- Cheap, precise, lightweight
- Magnet + Hall effect sensor
  - "Hall effect": moving wire past a magnet induces electric field
- Can be absolute or incremental
- Equivalent to stripes (the marker) and camera (the sensor) in optical encoders



en.wikipedia.org/wiki/Hall_effect_sensor, www.mathworks.com/help/physmod/sm/mech/ref/revolute.h 24

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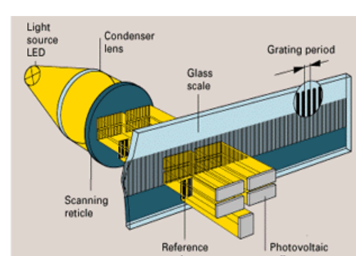
Wheel / Motor Encoders (2)



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Odometry and Localization

- The **localization** problem: where is the robot?
  - Odometry: figuring it out without environment cues
- Why not just look around?
  - Requires knowledge of the map
  - Often we are discovering it as we go, so that's uninformative
  - (Later: the **mapping** problem: building (or using) a map of the environment)
- Heading + approximate velocity = position estimate
  - (Eventually we'll get to SLAM: Simultaneous Localization And Mapping)

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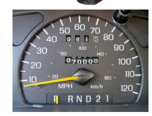
Odometry (Dead Reckoning)

- The robot can move
- So where am I? ← this is known as localization
  - Use proprioceptive sensors to estimate location
- Dead reckoning
  - Given motion sensors or known commands, estimate change in position over time
  - Sensitive to errors due to sensor inaccuracies, integration of velocity measurements over time, equipment calibration



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Heading Sensors

- Heading: direction robot is facing
  - With respect to some frame of reference
- Estimate of robot's orientation (x,y) + inclination (z)
- Proprioceptive heading sensors
  - Gyroscope, inclinometer
- Exteroceptive heading sensors
  - Compass, sundial
- But to understand headings…

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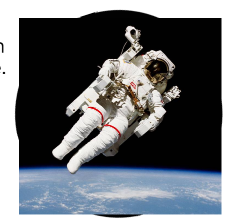
Frames of Reference

- A FoR is a coordinate system, plus anchor points
- So what does that mean?
  - Imagine someone floating in an infinite, featureless space.
  - Which way is she facing?
  - Is she moving?
- What about now?
  - The Earth gives us a **frame of reference**
- The frame is the space in which she is oriented



https://www.nasa.gov/mission_pages/shuttle/multimedia/mmu_eva.html

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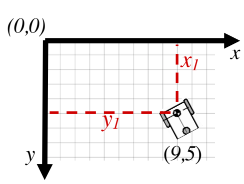
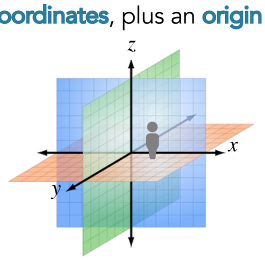
More Formally

- A frame of reference is a **coordinate system** plus one or more points that locate and orient it
- x, y, and sometimes z **coordinates**, plus an **origin**





en.wikipedia.org/wiki/Frame_of_reference, study.com/academy/lesson/coordinate-system-in-geometry-definition-types.html

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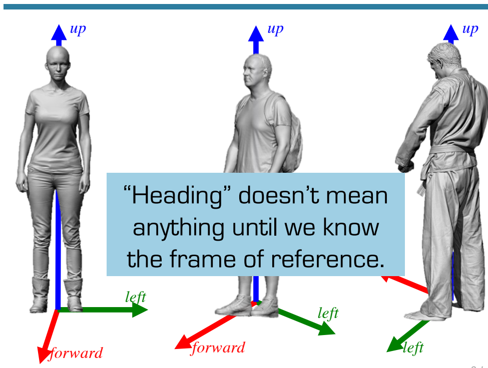
Comparing Frames of Reference



3dscanstore.com

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Heading: Compasses

Han dynasty "South pointer"

- Used since at least 2000 B.C.
  - Absolute measure for orientation
- Many ways to measure Earth's magnetic field
  - Mechanical magnetic compass
  - Direct measure of magnetic field (Hall effect sensor, magnetoresistive sensors)
  - Hang piece of magnetite from thread
- Major drawbacks:
  - Weakness of the field
  - Easily disturbed by magnetic objects or other sources
    - Not typically feasible for indoor environments

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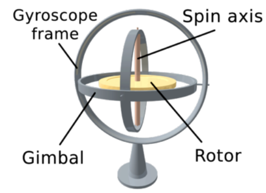
Heading: Gyroscope

- Heading sensors that read orientation
  - Absolute measure of heading of a mobile system
- Mechanical or optical



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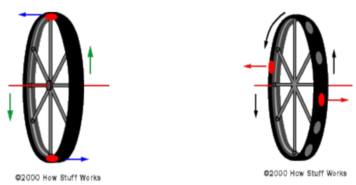
Mechanical Gyroscopes



- Newton's First Law: Every object in a state of uniform motion tends to remain in that state of motion unless an external force is applied to it
- Which means that trying to move it is resisted

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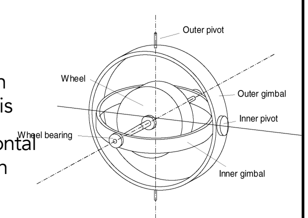
Mechanical Gyros

- Concept: inertial properties of a fast spinning rotor
  - "Gyroscopic precession"
  - Angular momentum of spinning wheel keeps axis of gyroscope stable
- Quality: 0.1° in 6 hours (!)
- If spinning axis is aligned north-south, earth's rotation doesn't affect horizontal axis
- If it points east-west, horizontal axis reads the earth rotation



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Optical Gyroscopes

- First commercial use:1980's on airplanes
- Optical gyroscopes
  - Angular speed (heading) sensors using two laser beams
- One is traveling clockwise, the other counterclockwise, around a cylinder
- Laser beam traveling in direction of rotation
  - Slightly shorter path → shows a higher frequency
  - Difference in frequency Δf of the two beams is proportional to the angular velocity Ω of the cylinder
- Needs very precise time measurement

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Location: Beacons

- Guiding devices with precisely known position
- Used since humans started to travel
- Natural beacons (landmarks): stars, sun, mountains, "that one weird tree"
- Artificial beacons: lighthouses

Sextant
(AKA: "Why sailors are depicted with eyepatches")

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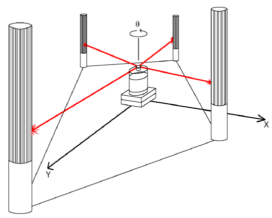
Ground-Based Beacons

- Active or passive?
  - Beacon has reflective tape and robot has a camera?
  - Infrared beacons?
- Major drawback: Requires instrumenting environment
  - Limits flexibility and adaptability to novel or dynamic environments
  - Costly and sometimes infeasible



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Global Positioning System

- 24 satellites (including three spares)
  - Orbit earth every 12 hours at a height of 20.190 km
  - Four in each of six planes inclined 55° wrt. earth's equator
  - Location of any GPS receiver is determined through a time of flight measurement
- Technical challenges:
  - Time synchronization between individual satellites and GPS receiver
  - Real time update of the exact location of the satellites
  - Precise measurement of the time of flight
  - Interferences with other signals

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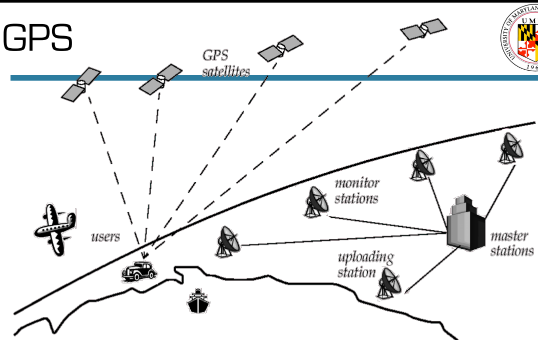
GPS



- Commercial GPS → accurate position down to ~2 meters
  - < 15 meters used to be encrypted, military-only signal

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GPS

- Time synchronization:
  - Atomic clocks on each satellite
  - Monitored from different ground stations
- Real time update of exact location of satellites:
  - Master station analyses all measurements, transmits actual position to each satellite
- Ultra-precise time synch extremely important
  - Electromagnetic radiation propagates at light speed
    - Roughly 0.3 m per nanosecond
  - Accuracy proportional to precision of time measurement

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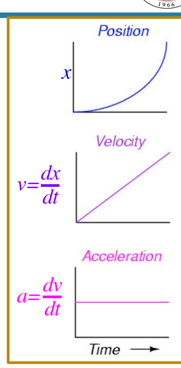
Physics of Localization

- Derivative of **position** x with respect to time is **velocity** v

You *do* need to understand this conceptually.
You *don't* need to do integrals or derivations on exams.

- So, given time + acceleration or velocity, we integrate to get position $x = \int v(t)dt = \iint a(t)dt$



https://www.youtube.com/watch?v=PDhLLURJSFI 45

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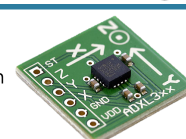
Accelerometers

- Measure acceleration forces
  - Could just track encoder information
  - …if you have wheels!
  - So how does your phone know whether it's in landscape or portrait mode?



- Piezoelectric accelerometer
  - Microscopic crystal structures stressed by acceleration
  - This creates a voltage that can be measured
- Capacitive accelerometer
  - Crystal stress can create a measurable change in capacitance

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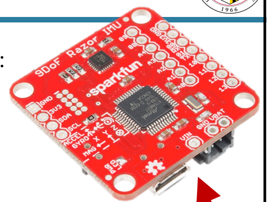
IMUs

- Inertial Measurement Units: report **motion**
  - Linear motion (direction, velocity/acceleration)
  - Angular motion (rotational direction/speed)
- Simple implementation: three gyroscopes plus three accelerometers
  - Gives you all of x, y, and z
- Even easier implementation: buy from Sparkfun



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Exercise

- You are building a mail delivery robot for the CSEE department
  - One floor, cubbyhole mailboxes
  - All doors are open
- Assume a manipulator arm
- No limits on battery/etc
- 2-4 people
  - **Write down each others' names!**
- Sketch out a design!
- The **structure** of the robot
  - How does it move?
    - Wheels? Legs? How big? How many?
  - What's attached where?
  - Size, speed, ..?
- All **sensors**
  - Include encoders etc.
  - Where are they on the robot?
  - (You will need at least 5, probably more like 15+)

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